

## Dark Matter and Particle Physics

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## ABSTRACT

Astrophysicists now know that 80% of the matter in the universe is ‘dark matter’, composed of neutral and weakly interacting elementary particles that are not part of the Standard Model of particle physics. I will summarize the evidence for dark matter. I will explain why I expect dark matter particles to be produced at the CERN LHC. We will then need to characterize the new weakly interacting particles and demonstrate that they are the same particles that are found in the cosmos. I will describe how this might be done.

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# 1 Introduction

One of the themes of the history of physics has been the discovery that the world familiar to us is only a tiny part of an enormous and multi-faceted universe. From Copernicus, we learned that the earth is not the center of the universe, from Galileo, that there are other worlds. More recently, Hubble's extragalactic astronomy taught us that our galaxy is a tiny part of an expanding universe, and the observation of the cosmic microwave background by Penzias and Wilson revealed an era of cosmology before the formation of structure. Over the past ten years, astronomers have recognized another of these shifts of perspective. They have shown that the stuff that we are made of accounts for only 4% of the total content of the universe. As I will describe, we now know that about 20% of the energy in the universe takes the form of a new, weakly interacting form of matter, called 'dark matter'. The remaining 75% of the energy of the universe is found in the energy content of empty space, 'dark energy'.

Dark energy is the most mysterious of these components. Its story is described in the article of Turner in this volume [1]. Dark matter, though, is the component that most worries the imaginations of particle physicists. What particle is this dark matter made of? Why have we not discovered it at our accelerators? How does it fit together with the quarks, leptons, and bosons that we have spent our lives studying?

And, conversely, dark matter is the component that most excites us by the possibility of its discovery. There are strong arguments that the next generation of particle accelerators, beginning next year with the Large Hadron Collider (LHC) at CERN, will produce the elementary particles of which dark matter is made. How can we recognize them? How can we prove that these particles are the ones that are present in the cosmos? And, finally, how can we use this knowledge to image the dark matter structure of the universe? I will address all of these questions in this article.

# 2 Evidence for Dark Matter

Although the astronomical picture of dark matter has become much clearer in the last ten years, the evidence for dark matter goes back to the early days of extragalactic astronomy. The evidence for dark matter is summarized in a beautiful 1988 review article by Virginia Trimble [2]. I will describe the most telling elements here.

In 1933, Fritz Zwicky measured the mass of the Coma cluster of galaxies, one of the nearest clusters of galaxies outside of our local group [3]. Zwicky's technique was to measure the relative velocities of the galaxies in this cluster from their Doppler shift, use the virial theorem to infer the gravitational potential in which these galaxies were moving, and compute the mass that must generate the potential. He found this mass to be 400 times the mass of the visible stars in galaxies in the cluster. The observation was soon confirmed by similar measurements of the Virgo cluster by Smith [4].

We now know that most of the atoms in clusters of galaxies are not seen in observations with visible light. Because these clusters generate enormously deep gravitational potential wells, it is easy for hydrogen gas from the galaxies to leak out and fill the whole volume of the cluster. These atoms acquire large velocities and emit X-rays when they collide. X-ray images show the clusters as glowing balls of gas. This does not remove the mystery, however, The X-ray emitting gas accounts for at most 20% of the mass of the cluster and cannot explain the origin of the deep potential well [5]. For this, we must postulate that the clusters are also filled with a new, invisible, weakly interacting form of matter.

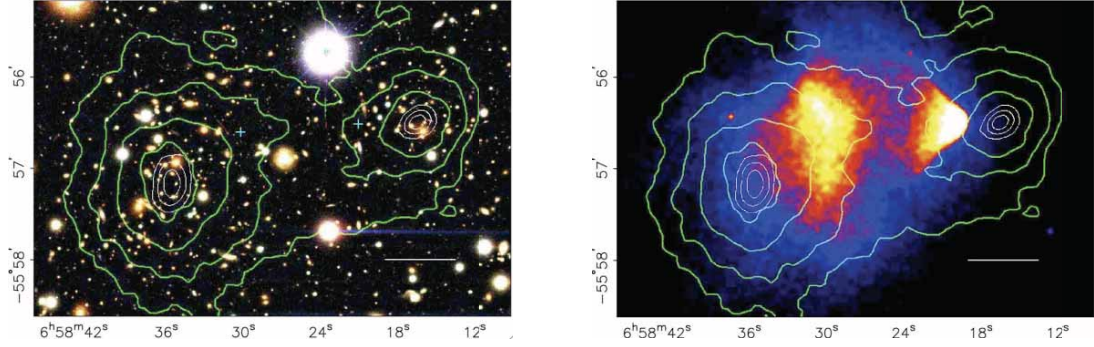


Figure 1: Images of the bullet cluster, 1E0657–558: optical image from the Hubble Space Telescope, X-ray image from the Chandra telescope, and mass density contours from gravitational lensing reconstruction [11].

In the 1970's, astronomers began to systematically measure the rotational velocity profiles or *rotation curves*, for many galaxies. One would expect that the mass of a galaxy is concentrated in the region where the stars are visible. Then, outside this region, Kepler's law would predict that the velocities should fall off as  $1/\sqrt{r}$ . In fact, the velocities are seen to be constant or even slightly increasing [6]. In the galaxy NGC 3067, using hydrogen gas lit up by a background quasar, Rubin, Thonnard, and Ford showed that the rotational velocity profile maintains its large value at a distance of 40 kpc (120,000 light-years) from the center of the galaxy, even though the visible stars become rare outside of 3 kpc [7]. From measurements of the velocities of globular clusters, it was found that the rotation curve of our own galaxy is also flat out to distances of 100 kpc from the center [2].

Detailed measurements of cosmic microwave background, including not only the averaged intensity of this background radiation but also its fluctuation spectrum, give additional information on dark matter. The microwave background was emitted at the time of *recombination*, when the hydrogen filling the universe, at a temperature of about 1 eV, converted from an ionized plasma to a transparent neutral gas. From the Fourier spectrum of fluctuations of the background radiation, it is possible to measure the dissipation of this medium. The most recent measurements from the WMAP satellite require a medium in which only 20% of the matter is hydrogen gas and 80% is composed of a very weakly interacting species in nonrelativistic motion [8]. These measurements can be converted to the current fractions of atomic and dark matter in the total energy of the universe,  $\Omega_i = \rho_i/\rho_{tot}$  [9]

$$\Omega_{at} = 0.042 \pm 0.003 \quad \Omega_{DM} = 0.20 \pm .02 \quad (1)$$

In all of these systems, dark matter is observed only through its gravitational influence. One might wonder, then, whether it is possible to explain the observations by modifying the law of gravity rather than by introducing a new form of matter [10]. The interpretation in terms of a new form of matter was recently boosted by the observations shown in Fig. 1. These pictures show three images of the galaxy cluster 1E0657–558 [11]. The first is the optical image, showing the galaxies that, as we have discussed, make up only a few percent of the mass of the cluster. The second picture shows the X-ray image from the Chandra telescope. This image shows where the bulk of the gas in the cluster is located. The superimposed contours show the total density of the mass in the cluster, as measured by gravitational lensing. It is remarkable that the peaks of the mass distribution occur where there are very few atoms. In this object, which probably arose from a collision of two clusters of galaxies, the atomic matter and the dark matter have become spatially separated. The observations cannot be explained by an altered law of gravity centered on the atoms. They require dark matter as a new and distinct component.

### 3 The WIMP model of Dark Matter

Thus, dark matter exists. What is it made of? In the Standard Model of particle physics, we know no neutral heavy elementary particles that are stable for the lifetime of the universe. Let us postulate a new species of elementary particle to fill this role. Bahcall called this a Weakly Interacting Massive Particle (WIMP). I would like to add one more assumption: Although it is stable, the WIMP can be produced in pairs (perhaps with its antiparticle), and it was produced thermally at an early time when the temperature of the universe was very high. WIMPs must also annihilate in pairs. I will assume that these processes established a thermal equilibrium.

These assumptions lead to an attractive theory of dark matter whose consequences I will explore in the remainder of this article. There are other models of dark matter that do not fit into this paradigm. A comprehensive review of dark matter models has recently been given by Bertone, Hooper, and Silk [12].

Using the WIMP model, we can build a quantitative theory of the density of dark matter in the universe. As the universe expanded and cooled, the reactions energetic enough to produce WIMPs became more rare. But at the same time, WIMPs had more difficulty finding partners to annihilate. Thus, at some temperature  $k_B T_f$ , they dropped out of equilibrium. A small density of WIMPs was left over. At this era, the energy density of the universe was dominated by a hot thermal gas of quarks, gluons, leptons, and photons, with a total number of degrees of freedom  $g_* \approx 80$ . Using this thermal density to fix the expansion rate of the universe as a function of time, we can determine the evolution of the WIMP density by integrating the Boltzmann equation. It is convenient to normalize the WIMP density to the density of entropy, since in standard cosmology the universe expands approximately adiabatically. Then one finds [13]

$$\Omega_{DM} = \frac{s_0}{\rho_{tot}} \left( \frac{\pi}{45g_*} \right)^{1/2} \frac{k_B T_f / mc^2}{m_{Pl} / \hbar^2 \cdot \langle \sigma v \rangle} \quad (2)$$

where  $s_0$  and  $\rho_{tot}$  are the current densities of entropy and energy in the universe,  $m_{Pl}$  is the Planck mass, equal to  $\hbar c / \sqrt{G_N}$ , and  $\langle \sigma v \rangle$  is the thermally averaged annihilation cross section of WIMP pairs multiplied by their relative velocity. In the equation that determines  $T_f$ , this temperature appears in a Boltzmann factor  $e^{-mc^2/k_B T_f}$ , where  $m$  is the WIMP mass. Taking the logarithm, one finds  $k_B T_f / mc^2 \approx 1/25$  for a wide range of values of the annihilation cross section.

With this parameter determined, we know all of the terms in (2) except for the value of the cross

section, and so we can solve for this factor. The result is

$$\langle\sigma v\rangle = 1 \text{ pb} \tag{3}$$

A particle physicist would recognize this value as the typical size of the production cross sections expected for new particles at the LHC. More generally, if we assume that the coupling constant in the WIMP interactions is roughly same size as the dimensionless coupling  $\alpha$  that gives the strength of weak and electromagnetic interactions, this cross section results from an interaction mediated by a particle whose mass is of the order of 100 GeV.

This result is remarkable for two reasons. First, it allows us to transform our astrophysical knowledge of the cosmic density of dark matter into a prediction of the mass of the dark matter particle. Second, that prediction picks out a value of the mass that is very close to the mass scale associated with the Higgs boson and the symmetry breaking in the weak interactions. In an earlier article in this volume, Okada has argued that we should expect to find new elementary particles at that mass scale [14]. Perhaps these new particles are in some way responsible for the dark matter.

In fact, explicit models of symmetry breaking in electroweak interactions often provide a natural setting for dark matter. Supersymmetry, discussed in the article of Yamaguchi in this volume [15], predicts a new boson for each known fermion in Nature, and vice versa. It is natural that the fermionic partner of the photon is its own antiparticle, so that it is stable but annihilates in pairs. This particle is then a perfect candidate for the WIMP. Other models of electroweak symmetry breaking also contain new neutral weakly-interacting particles that can be made stable by natural symmetry principles.

## 4 Production and Detection of WIMPs at the LHC

If the mass of the WIMP should be about 100 GeV, we should be able to produce WIMPs if we can build an accelerator that provides elementary particle collisions at energies higher than 100 GeV. However, it is not so straightforward. A WIMP, being as weakly interacting as a neutrino, passes through a typical elementary particle detector unseen. It is only from the properties of the other particles produced in association with the WIMP that we can recognize these events and select them for analysis. Particle physicists have analyzed in some detail how to do this. Most of the specific analysis has been done in models of supersymmetry, so, for concreteness, I will use that picture here. The general conclusions apply to WIMPs in many other models of weak interaction symmetry breaking.

Supersymmetry predicts many new elementary particles in addition to the WIMP. In particular, the gluon of QCD has a fermionic partner, the *gluino*, and the quarks have bosonic partners, called *squarks*. Gluinos and squarks carry the same conserved quantum number that keeps the WIMP stable. They are expected to be heavier than the WIMP and to decay to the WIMP by emitting quarks, leptons, and Standard Model bosons. Events with squark or gluino pair production, then, will have a characteristic form. Many energetic quarks and leptons will be emitted, but also each event will end with the production of two WIMPs that make no signal in the detector. The observable particles in the event will show an imbalance of total momentum. The missing momentum is that carried off by the WIMPs.

We have not yet seen events of this type at currently operating accelerators. The highest-energy accelerator now operating is the Tevatron collider at Fermilab, and the experiments there put lower limits of about 300 GeV on the masses of gluinos and squarks [16]. In 2008, however, the LHC will begin operation with proton-proton collisions at a center of mass energy of 14000 GeV. Not all of

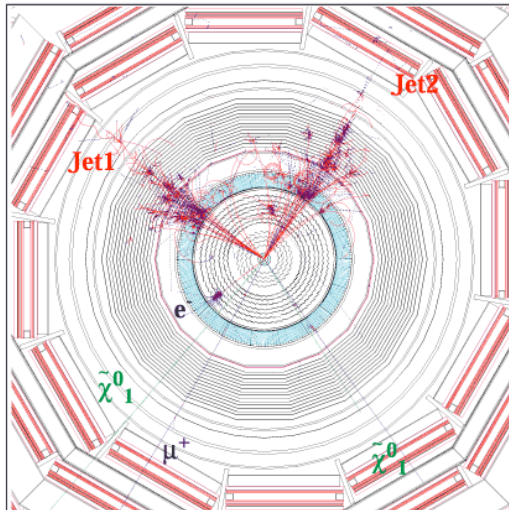


Figure 2: Simulated LHC event, with pair production of gluinos and the decays of these particles to WIMPs, as would be observed by the CMS experiment at the LHC [17]. The apparent imbalance of momentum transverse to the beam axis is due to the WIMPs (denoted  $\tilde{\chi}_1^0$  in the figure), which produce no signals in the detector.

this energy is available for production of supersymmetry particles. The proton, after all, is a bound state of quarks and gluons. Gluinos and squarks are produced in collisions of individual quarks and gluons, which typically carry 10% or less of the total energy of the proton. Still, we expect to see collisions with total energy above 2000 GeV at a significant rate. This implies that squark and gluon pair production, leading to events with WIMPs, can be seen over almost all of the parameter space of the model. Figure 2 shows a simulation of a characteristic event of this type, as it would be observed by the CMS detector at the LHC [17].

## 5 Recognizing the Mass of the WIMP

The discovery of events at the LHC with apparent unbalanced momentum will signal that this accelerator is producing weakly interacting massive particles. However, it would be far from clear that this particle is the same one that is the dominant form of matter in the universe. To demonstrate this, we would need to correlate properties of the WIMP that we observe at the LHC with astrophysical observations. This will probably first be done through measurements of the mass of the dark matter particle. Using detailed measurements of the kinematics of quarks and leptons in the LHC events, it is expected that the mass of the WIMP produced there will be measured to 10% accuracy [18]. We then must compare this value with measurements of the mass of the cosmic WIMP. To do this, it is necessary to detect the dark matter in the galaxy, not as a distribution of gravitating mass, but as individual particles.

There are two strategies to make this detection. The first, reviewed by Spooner in his article in this volume [19], is to place very sensitive detectors in ultra-low background environments and look for rare events in which a WIMP in our cosmic neighborhood falls to earth and scatters from an atomic nucleus in the detector. The cross section for this process is expected to have the remarkably

small value of 1-10 zeptobarns, but in the next few years semiconductor and liquid noble gas detectors in deep mines are expected to reach this level of sensitivity. The mean energy deposited in these events depends on the WIMP mass  $m$  and the target nucleus mass  $m_T$  roughly as

$$\langle E \rangle = \frac{2v^2 m_T}{(1 + m_T/m)^2} . \quad (4)$$

Then, for a 100 GeV WIMP, detection of 100 scattering events would lead to a mass determination at roughly 20% accuracy [20, 21].

The second strategy is to look for WIMP annihilations in our galaxy. Although the density of WIMPs is sufficiently small that WIMPs cannot annihilate frequently enough to affect the overall mass density of the universe, WIMPs still should annihilate at a low rate, especially in places where their density is especially high. Astrophysicists understand the formation of galaxies and larger structures in the universe as arising from the clumping of dark matter as a result of its gravitational attraction. So our galaxy, and especially the center of the galaxy, should be a place with a relatively high density of WIMPs and thus a higher rate of WIMP annihilations. In an individual WIMP annihilation, the two WIMPs produce two showers of quarks, which are observed mainly as pions and photons. The pions and other charged particles are bent by the galactic magnetic field. But the photons, energetic gamma rays, fly outward in a straight line from the annihilation point. A gamma ray telescope can observe these photons and measure their energy spectrum. The spectral shape is characteristic, with a sharp cutoff in energy at the mass of the WIMP [22]. The galaxy is expected to contain clumps of dark matter that should show up as spots bright in gamma rays with no counterpart in optical radiation. These spots should be intense enough to be seen with the gamma ray telescope satellite GLAST, and, if the WIMP mass is greater than several hundred GeV, by new ground-based gamma ray telescopes. Measurement of the endpoint of the energy spectrum should give a second astrophysical determination of the WIMP mass to 20% accuracy.

If the mass of the WIMP seen at the LHC is the same as the mass from astrophysical detection experiments, this will provide strong evidence that the LHC is producing the true particle of dark matter.

## 6 Predicting the Properties of the WIMP

To provide additional evidence on the identity of the WIMP observed at the LHC, we would like to assemble enough data about this particle to predict its pair annihilation cross section. From (2), we see that knowledge of this cross section from particle physics would give a prediction of the cosmic density of dark matter. It will be very interesting to compare that prediction to the value of the dark matter density obtained from cosmic microwave background measurements. Agreement of these values would not only confirm the identity of the WIMP. It would also verify the standard picture of the early universe up to the temperature  $T_f$ , corresponding to a time in the early universe about  $10^{-9}$  seconds after the Big Bang.

It is quite a challenge to predict the WIMP pair annihilation cross section. At the minimum, this requires measuring the masses and couplings of the heavier particles that are exchanged in the process of WIMP annihilation. In supersymmetry, WIMP annihilation is often dominated by the exchange of the bosonic partners of leptons, which must be identified through their decays to leptons and missing momentum. An alternative mechanism for WIMP annihilation is the exchange of the fermionic partners of the weak interaction bosons  $W$  and  $Z$ . These cross sections depend sensitively on the mixing angles that determine the exact mass eigenstates of these particles. If several different reactions can contribute, the parameters of each must be measured or bounded.



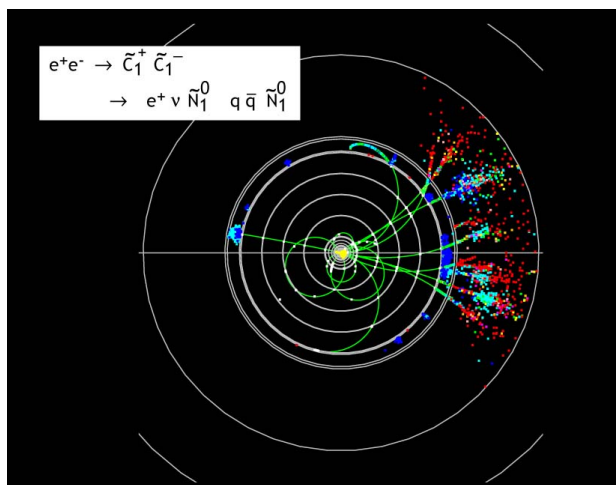


Figure 3: Simulated ILC event, with pair production of the supersymmetric partners of  $W$  bosons and subsequent decay to quarks, leptons, and WIMPs [24]. Only the visible products are shown in the figure.

Detailed studies of this program in a variety of supersymmetry models show that it requires more precise knowledge of the parameters of the model than can be obtained from the LHC. Fortunately, there is another technique for producing and studying new elementary particles that is capable of achieving higher precision. Electron-positron annihilation at high energy can create pairs of the new particles in a controlled setting, through reactions that are much simpler than those that we expect at the LHC. This process will be studied at the future electron-positron collider ILC discussed in the contribution of Yamamoto to this volume [23]. A simulated supersymmetry production event at the ILC is shown in Fig. 3.

Once we have measured the masses of supersymmetric particles with high precision and also measured the cross sections that determine their couplings and mixing angles, we will be able to put forward a prediction of the cosmic dark matter density from particle physics data that can be compared to astrophysical measurements. Recently, Baltz, Battaglia, Wizansky, and I discussed quantitatively how accurate such microscopic predictions could be. Starting from a set of supersymmetry models with a variety of different mechanisms for WIMP annihilation, we analyzed the accuracy of measurements on supersymmetric particles that could realistically be expected from the LHC and from the ILC and derived from these the accuracy of the prediction to be expected for the dark matter density [25]. Figure 4 shows our results for two of these models, expressed as the likelihood distribution for  $\Omega_{DM}$  predicted from the collider data that would be expected from LHC, from ILC measurements at the design energy of 500 GeV, and from an upgraded ILC running at an energy of 1000 GeV. Other groups have found similar results for first of these models [26, 27]. These predictions will be compared to the cosmic microwave background results from the next-generation experiments, which should determine  $\Omega_{DM}$  to the percent level [28]. It will take some time to collect all of the data required, but eventually we will have this sharp test of the WIMP identity of dark matter.

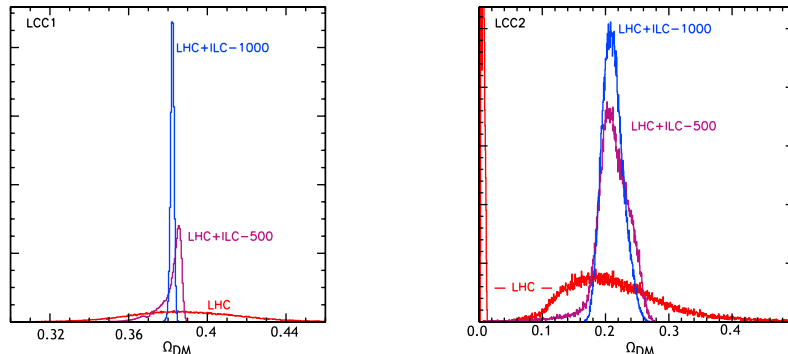


Figure 4: Predictions of  $\Omega_{DM}$  from collider data [25]. Each figure was generated by assuming a specific supersymmetry model of the WIMP, working out the set of measurements that would be made to determine the spectrum of supersymmetry particles—at the LHC, at the ILC, and at an upgraded ILC at 1000 GeV in the center of mass—and determining the cosmic density of WIMPs from this data. The figure gives the likelihood distribution of the prediction in each model; the accuracy of the collider measurements determines the spread in the predictions.

## 7 The WIMP Profile of the Galaxy

Once we have established the identity and properties of the WIMP, these results should feed back into astronomy. I noted in Section 2 that it is possible to detect dark matter on cluster scales and to map its distribution using gravitational lensing. However, for dark matter in the galaxy, the gravitational bending of light is not large enough effect to provide structure information. To see where the dark matter is in our galaxy, we need to map dark matter particles.

The distribution of dark matter in the galaxy is still mysterious, and in fact is one of the most controversial questions in astrophysics. In the cold dark matter model of structure formation, a galaxy as large as ours must be built from the assembly of smaller clusters of dark matter. The smaller clusters merge through their gravitational interaction, disrupt one another tidally, and eventually smooth out to form the halo of the galaxy. The time required for this evolution is on the order of the current age of the universe. Thus, most cold dark matter theories predict that the halo of the galaxy is inhomogeneous. A model of the density distribution of dark matter in a model galaxy, based on the clustering model of Taylor and Babul [29] is shown in Fig. 5. An especially large clustering of dark matter should occur at the center of the galaxy. Some models predict caustics with large, almost singular dark matter densities; other models predict smoothing of the dark matter below some scale. Understanding the true situation will bring us closer to understanding how our galaxy and the others in the universe were born and evolved [31].

The determination of the properties of the dark matter particle will give us the information that is needed to predict the interaction rates of dark matter particles with ordinary matter and with one another. This in turn will allow us to interpret detection signals in terms of the absolute density

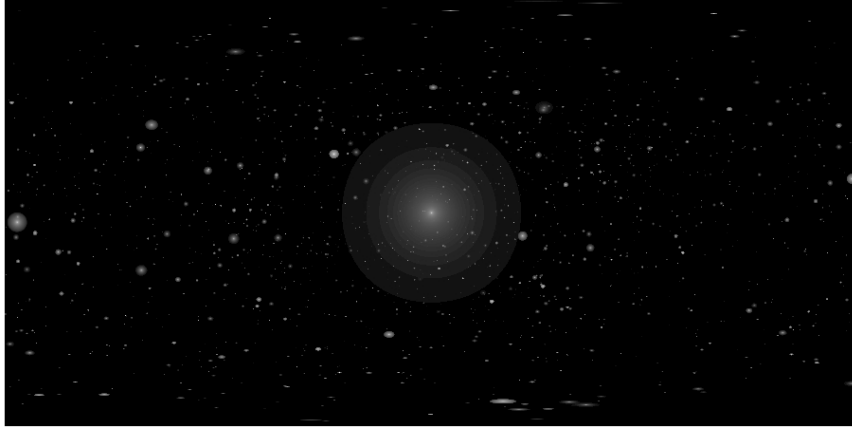


Figure 5: Dark matter distribution in a model galaxy, according to the simulation of Taylor and Babul [29]. This visualization, done by Baltz [30], shows a map of the column density of dark matter along each line of sight. This quantity gives the brightness with which each cluster of dark matter shines in annihilation gamma rays.

of dark matter both here and elsewhere in the galaxy. By dividing the underground detection rate for dark matter by the interaction cross section determined from collider data, we will be able to measure the absolute flux of dark matter at our position in the galaxy. By measuring the luminosity of clumps of dark matter in the galaxy and dividing by the dark matter annihilation cross section determined from collider data, we will be able to map at least the largest clumps of dark matter in terms of their absolute density.

## 8 Conclusions

Today, dark matter is one of the great mysteries of physics and astronomy. But I have argued in this article that the time is approaching for its solution. I have motivated the idea that dark matter is composed of a new elementary particle, the WIMP, whose mass is about 100 GeV. If this is true, then over the next five years we should produce the WIMP at the LHC, and we should see signals of astrophysical WIMPs in several different detection experiments. This will set in motion a campaign to determine the properties of dark matter by measurements both in high-energy collider experiments and through mapping of astrophysical signals. Over the next fifteen years, we will learn the story of this major constituent of the universe, its identity, its properties, and its role in our cosmic origin.

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